Wrist-located pulse detection using IR signals, activity and nonlinear artifact cancellation

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Abstract — **We present a new integrated device for monitoring heart rate at the wrist using an optical measure. Motion robustness is obtained by using accurate motion reference signals of 3D low noise accelerometers together with dual channel optical sensing. Nonlinear modelling allows to remove the motion contributions in the optical signals and the spatial diversity of the sensors is used to remove reciprocal contributions in the two channels. Finally a statistical estimation, based on physiological properties of the heart, gives a robust estimation of the heart rate. Qualitative and quantitative performance evaluation of the performances on real signals clearly show that the proposed system gives an accurate estimation of the heart rate, even under intense physical activity.**

1 Introduction

Portable heart rate monitoring devices are classically composed of a processing device and an external probe (*e.g.* electronic stethoscope, optical measure at ear lobe, chest belt for ECG based measurement, etc.). The use of an external probe is often considered as a reduction of the comfort. In this paper we propose a new fully integrated measurement system[1] that is located at the wrist. This system is based on dual-channel optical measurement of the subcutaneous blood flow, accurate measure of the motion provided by accelerometers and advanced signal processing techniques to obtain robust and reliable estimation of the heart rate. The optical measure is based on photoplestysmography (PPG), which has been used widely over the past for the estimation of cardiovascular parameters such as for example pulse oximetry and heart rate [1]. Corruption of the PPG signal arises from influences of ambient light and motion of the subject. These artifacts lead to erroneous interpretation of PPG signals and degrade the accuracy and reliability of PPG-based algorithms for the estimation of cardiovascular parameters.

Processing of ambient light artifact is not critical because the influence of ambient light can be measured using multiplexing techniques and the PPG signal can be restored using a subtractive-type techniques [2]. In contrast, processing of motion artifacts is a though task since its contribution exceeds often the contribution of the useful pulse-related signal by an order of magnitude. It is caused by mechanical forces that induces changes in the optical coupling and the optical properties of the tissue. Several methods have been proposed to reduce motion artifacts in PPG signals. Feature-based algorithms have been proposed to discard the corrupted segments from the signals [3]. This kind of approach allows one to reduce the occurrence of false-alarm in clinical environments, but it often degrades the signals with small motion artifact contributions. This could lead to erroneous estimation of cardiovascular parameters. In order to circumvent this drawback, model-based noise cancelling techniques have been applied more recently for the enhancement of optical signals [4, 5, 6, 7]. In such approaches a reference signal of motion is recorded and a parametric model is used subsequently to retrieve motion related influences in the optical signals [8]. Nevertheless, motion references are classically obtained by piezo-sensors or optical measures and convey therefore only incomplete or local information of motion. This degrades the performance of model-based noise cancelling techniques since they require complete and low-noise motion reference signal [8].

In the proposed approach, a fully integrated three dimensional accelerometer, developed within our company, is used to provide a reliable motion reference. The reliability of this reference signal is ensured by the high accuracy and very low noise of the accelerometer. To achieve efficient removal of motion related artifacts in the optical signals, nonlinear model-based techniques are applied. In order to grasp the spatial diversity of the optical characteristics of the tissue, two optical sensors are used. Eventually, the heart rate is estimated from the enhanced signals using inter-beat extraction based on physiological properties of cardiac cells and maximum likelihood histogram clustering of the resulting time series.

2 Physical model

The principle of the proposed method resides in emitting an optical infra-red (IR) signal at the surface of the body tissue. This signal is then propagated through the tissue where it is submitted to modifications due to reflection, refraction, scattering and absorption. The resulting signal, after propagation through the tissue is grasped by one or multiples optical sensors, which are located at distance of about 10 mm around the optical source. Since variations of optical tissue characteristics are related to variations in the subcutaneous blood flow, the received signal can be used for the estimation of the heart rate.

When light is transmitted through biological tissue, several mechanisms are involved in the interaction between the light and the tissue. These interactions are reflection, refraction, scattering and absorption. Reflection and refraction occur at the interfaces between the probe and the subject. Scattering is due to the microscopic variations of the dielectric properties of the tissue. These variations are due to the cell membranes and the subcellular components (*e.g.* mitochondria and nuclei). For infra-red (IR) light, the absorption is mainly due

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Abstract

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to chromophores such as hemoglobin, myoglobin, cytochrome, melanin, lipid, bilirubin and water. The relative importance depends on the wavelength considered and their distribution in the tissue.
Under ideal steady-state condition, the received IR light signal contains both a constant and a time varying component. The constant component is generally ascribed to baseline absorption of blood and soft tissue, non expansive tissue such as bone, as well reflectance loss [6]. The varying component reflects the modification of the effective path length due to the expansion of the tissues subject to the varying blood pressure.
For the near IR wavelength, the light propagation into the tissue is governed by scattering and absorption [9]. The *Beer-Lambert* equation is generally used to describe the phenomenon of light absorbtion in biological tissue [6]:

$$I_o(t) = I_i(t) \cdot \exp\left(-\sum_{j=1}^{n} \epsilon_{\lambda,j} c_j(t) d_j(t)\right) \qquad (1)$$

where I_i and I_o are the input and output light intensity, λ is the wavelength of light and c_j, $d_j(t)$ and $\epsilon_{\lambda,j}$ represent, respectively, the concentrations, the spanning path length and the absorption coefficient of the different components.
Voluntary or involuntary movements corrupt the PPG signal and create motion related artifacts. It is generally accepted that motion artifacts are mainly due to modification of the optical properties of the tissue (modification of blood pressure, modification of the optical path, etc.) [10]. These modifications affect the corresponding components of the Beer-Lambert equation (Eq. 2). Therefore, in presence of motion artifact, the received intensity can be rewritten in function of the major contributions:

$$I_o(t) = I_i(t) \cdot \gamma_{tissue} \cdot \gamma_{pulse}(t) \cdot \gamma_{gravitiy}(t) \cdot \gamma_{motion}(t) \qquad (2)$$

where γ_{tissue} is the static attenuation due to the tissue, $\gamma_{pulse}(t)$ is due to pulsatile absorption of the blood, $\gamma_{gravity}(t)$ is due to change of position and $\gamma_{motion}(t)$ is due to the dynamic changes of the tissue induced by the movement of the arm. It is obvious that the different contributions becomes additive if one takes the logarithm of Eq. 2.
When the subject is static, only the contribution of $\gamma_{pulse}(t)$ changes with the time and it is then straightforward to remove the other contributions using a high-pass filtering. When the subject is moving the contribution of the gravity and the modification of the interface are varying with the time and they have to be removed from the signals in order to allow an accurate estimation of the heart rate. The contribution of the gravity are at low frequency and can be removed using an adaptation of the gain. The contribution of the motion is difficult to remove, especially if it is in the same frequency band as the heart rate. Therefore techniques have to be developed in order to the remove the motion artifact to obtain an accurate estimation of the heart rate.

3 Proposed method

A. *Global Description*

It as been shown above that IR-signals recorded at the wrist are mainly affected by perturbations, such as tissue modifications, motion and gravity related artifacts. The main issue of this work resides in the estimation of the mean heart rate from short time recordings of IR-signals (10 seconds). It is assumed that the tissue properties do not vary over the considered duration and for a dual channel approach the log-corrected observed IR-signals given by Eq. 2 can be written as:

$$\begin{aligned} y_1(t) &= s_1(t) + n_{m1}(t) + n_1(t) \\ y_2(t) &= s_2(t) + n_{m2}(t) + n_2(t) \end{aligned} \qquad t = 0, \ldots, N_t - 1$$

where $s_1(t), s_2(t)$ are pulse pressure related signal contributions, $n_{m1}(t), n_{m2}(t)$ are artifacts due to motion and gravity, $n_1(t), n_2(t)$ include measurement noise and non-modelled stochastic signal contributions and N_t is the number of observed samples. To obtain a robust pulse detection in a large variety of experimental conditions, namely non-stationary environment, the proposed method works on a frame-to-frame basis with a frame duration of 3 seconds and it consists of mainly of a three step algorithm (see Figure 1). In a first step, the two observed optical signals (y_1, y_2) are enhanced using nonlinear, model-based noise cancelling techniques [8, 11, 12]. The motion reference required by such techniques is obtained by a completely integrated three-dimensional accelerometer developed within our company. The high accuracy and sensibility of this accelerometer ensures reliable reference signals, which is essential in model based noise cancelling techniques [8]. The nonlinear modelling consists in a polynomial expansion model and an associated model selection based on the Minimum Description Length criterion (MDL) [11]. This avoids an overfitting of the time series and ensures in this way that no pulse pressure related signal contributions are cancelled. The goal of the second step is to remove measurement noise and non-modelled stochastic signal contributions in the two recorded channels. This is achieved by a noise reduction algortihm based on spatio-temporal principal component analysis (PCA) [13]. Additionally, spatio-temporal PCA allows one to reduce artifacts related to finger-movements, which are generally not cancelled in step 1. Indeed, finger movements do not necessarily imply a global displacement of the forearm and are therefore not grasped by the accelerometers. In contrast, finger movements imply often tiny, reciprocal tendon related displacement of the forearm tissue, which yields reciprocal artifact contribution in the two recording channels. Due to the reciprocity of the signal contribution they can efficiently be cancelled by a spatio-temporal PCA [13]. Eventually, the third step, resides in the pulse detection on the enhanced IR-signals. It consists of an inter-beat interval extraction achieved through a classical maximum detection procedure with inhibition of peak detection during a the refractory period of cardiac cells. Subsequently, a maximum likelihood histogram clustering of the resulting inter-beat intervals is performed [14]. In order to cope with highly non-stationary environments, inter-beat intervals of non-stationary segments are discarded. The stationarity is assessed through classification of the parameters of the nonlinear model throughout subsequent frames [15]. It has to be pointed out that this clustering technique allows one to eliminate outliers, cope with non-symmetric inter-beat interval distributions and construct a reliability measure of the estimated pulse. From the two enhanced signals, one can obtain two candidate signals for pulse detection, namely after PCA based enhancement of signal 1 and of signal 2. Eventually, a robust a reliable estimate of the pulse is obtained through a nonlinear mapping of the two candidate values in function of their reliability measures. The nonlinear mapping is achieved by multiple layer perceptron (MLP), which has been trained on data of various experimental setup [16].

B. *Parsimonious nonlinear Modelling*

A key element in the proposed algorithm is the nonlinear model, which provides an estimation of the motion related contributions in the observed IR-signals. The relationship between time varying optical characteristics and its influence on

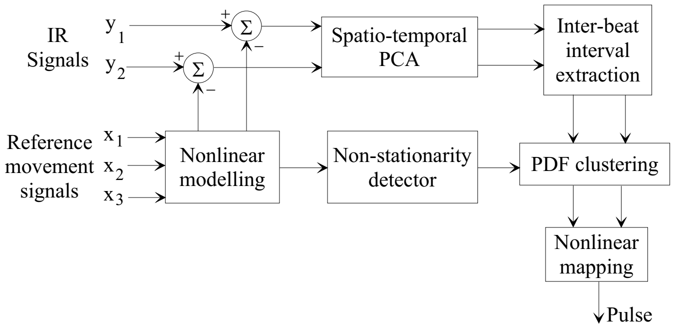

Figure 1: *The proposed dual channel pulse detection algorithm based on nonlinear model based motion artifact cancelling, coherence based reduction of measurement noise and stochastic signal contributions and a pulse detection using maximum likelihood histogram clustering .*

IR-signal is globally described by the Beer-Lambert law. Even though, one can obtain linear characteristics of these variations of the optical characteristics by a logarithmic transformation, their relationship to a global reference motion signal, such as the one grasped by the accelerometers is complex and may be nonlinear. In order to take into account of these potential nonlinear contributions, a third order polynomial moving average model NMA has been applied [11, 12]. Moreover, since the model includes a parsimonious selection criterion (MDL) together with an efficient search algorithm, linear terms are first tested first nonlinear higher order polynomial terms are only included if they are required for an efficient and parsimonious description of the data at disposal. Thus, due to the efficiency of the MDL-based parameter selection, overfitting of the time series is avoided and high model based noise reduction can be achieved.

C. Noise Reduction by Spatio-Temporal PCA

Noise reduction based on PCA has been shown to provide high enhancement performance in various applications [17, 18, 19]. To take simultaneously advantage of the spatial and temporal correlations existing between and within the observed noisy signals, spatio-temporal PCA has been applied. The basic idea behind PCA-based noise reduction is to observe the noisy data in a large m–dimensional space of delayed coordinates. Since noise is assumed to be random, it extends approximately in a uniform manner in all the directions of this space. In contrast, the dynamics of the deterministic systems underlying the data confine the trajectories of the useful signals to a lower–dimensional subspace of dimension $p < m$. Consequently, the eigenspace of the observed noisy mixtures is partitioned into a noise and a signal–plus–noise subspace and noise reduction is performed by projecting the noisy mixtures onto the signal-plus-noise subspace. The main problem in PCA-based noise reduction algorithms is the optimal choice of the parameters p and m. For the selection of the optimal PCA dimension m we can benefit from the fact that in the given biomedical application we are dealing with signals containing quasi–periodic contributions. The embedding dimension can therefore be estimated from the bandwidth of these quasi–periodic contributions [13]. On the other hand the choice of p is not critical in this application since we are looking mainly for one quasi–periodic contribution which is represented by $p = 2$.

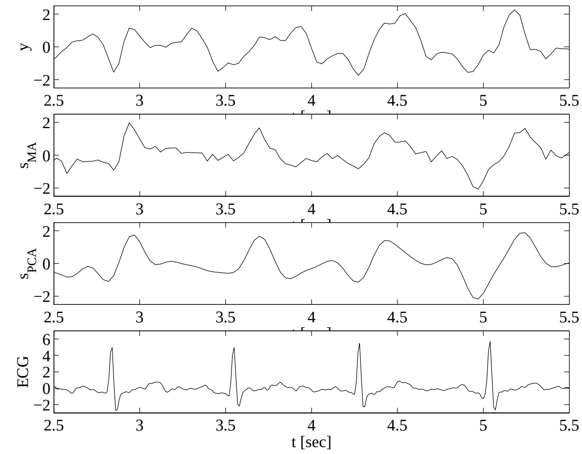

Figure 2: *Typical results for signal enhancement under physical activity. Represented are results for one channel: IR signal $y(t)$, signal after enhancement by MA modelling $s_{MA}(t)$, signal after enhancement by MA modelling and subsequent spatio-temporal PCA $s_{PCA}(t)$, and eventually the surface electrocardiogram ECG recorded for the validation of the method.*

4 Performance Assessment

In order to achieve an assessment of the performance of the proposed pulse detection device in natural environments qualitative and quantitative validations have been performed under various experimental conditions. The experimental protocol has been conducted on 5 subjects including resting baseline conditions Ba and physical activity Pa (running at 30, 60 and 90 movements per minute). Under each condition, 10 seconds of data have been recorded using the following system:

- *Optical probe:* The optical probe is composed of three elements: a light emitting device (LED) which constitutes the optical source. Two photo diodes located at each side of the LED in order to grasp the spatial diversity of the optical characteristics of the tissue.
- *Motion reference:* A fully integrated, low-power three dimensional accelerometer developed within our company, which provides low-noise reference signals of motion. probe.

Simultaneously, the surface electrocardiogram (ECG) has been measured for validation purposes. All the signals have been recorded at a sampling frequency of 500 Hz.

In order to illustrate the performance of our system in a qualitative way, a typical results of signal enhancement achieved by the proposed signal processing techniques is shown in Figure 2. One can easily observe that the recorded IR-signals ($y(t)$) are strongly affected by the movement related artifacts. Indeed, this IR-signal contains numerous peaks which can be associated to motion. Moreover, some pulse related peaks are displaced due to the influence of motion. After model based artifact cancelling pulse related peaks are recovered, while motion related contributions are discarded. Eventually, residual noise contributions due to tiny local movements not grasped by the accelerometers, modelling errors and other stochastic influences are removed by spatio-temporal PCA. Spatio-temporal PCA is well suited for this problem since it enhances contributions in the two signals obtained after model-based noise reduc-

	Baseline	Running
Relative error [%]	-0.7±1.4	1.6 ±9.5

Table 1: *Results of pulse estimation from IR signals under baseline conditions and physical activity. Represented are the mean value and standard deviation of the relative error for five subjects.*

tion while discarding non-correlated reciprocal contributions as the ones related to finger movements. A thorough analysis of the resulting signal $s_{PCA}(t)$ highlights that the information of inter-beat interval is recovered up to a delay, which can be associated to the applied signal processing techniques. The proposed multidimensional signal enhancement techniques paves thus the way to robust pulse detection in adverse motion disturbed environments.
A qualitative validation of the proposed pulse detection algorithm has been performed using the *ECG* as a reference. The mean value and standard deviation over all subjects and for the given experimental protocol are shown in Table 1. The analysis of these results underlines the robustness of the proposed pulse detection algorithm. Indeed, for resting baseline conditions the relative error is of about one percent. Under physical activity the mean value over all subjects increases only slightly, while the standard deviation remains nevertheless below ten percent. These results underline the robustness of the proposed approach since consistent and reliable pulse estimates are obtained under various experimental conditions. Eventually, it has to be pointed out that the application of nonlinear instead of linear modelling decreases the standard deviation of the detected heart rate of about one to two percent. This is mainly due to the inclusion of the parsimonious MDL-based model selection, which avoids an overfitting of the time series. Indeed, the full nonlinear model would retain pulse related components in the estimate of the motion artifact. Since these components are subtracted from the optical signals, the quality of the enhanced signal and consequently the reliability of the estimated pulse are reduced. In contrast, MDL selects only movement related parameters in the model, which yields higher enhancement performance and a more accurate pulse estimation in adverse noisy environments.

5 Conclusions

In this paper we have presented a new approach for the estimation of the heart rate using optical measure of the tissue at the wrist. The use of acceleration signals and nonlinear modelling techniques allows to obtain a reliable measure even in presence of motion artifacts. The main advantage of this technique is that the measurement device can be fully integrated into a watch, avoiding the need of an external probe as in actual systems. The results obtained clearly show that the proposed approach make it possible to develop a new kind of device for heart rate monitoring during physical activity.

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